Friction and Wear Characteristics of a Modified Composite Solid Lubricant Plasma Spray Coating

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Abstract

LCR304 is a solid lubricant coating composed of Ni-10Cr, Cr_2O_3, BaF_2-CaF_2 and Ag and developed for dimensional stability in high temperature air. This coating is a modification of PS304, which differs in that the Ni-Cr constituent contains 20wt% Cr. The tribological characteristics of LCR304 were evaluated by pin-on-disk and foil air bearing rig testing from 25° to 650°C and compared to previous test results with PS304. For both tests, the friction coefficient decreased as temperature increased from 25° to 650°C. Wear generally decreased with increasing temperature for all pin-on-disk tests. LCR304 coated components produced the least wear of Inconel X-750 counterface materials at 427 and 650°C. These results indicate that the LCR304 coating has potential as a replacement for PS304 in, for example, low cycle (minimum wear) applications where dimensional stability is imperative.

Key words: friction, wear, solid lubricants, plasma spraying, air bearings, gas bearings.

Introduction

PS304 is a composite solid lubricant coating developed at NASA Glenn Research Center for use in high speed, high temperature *Oil-Free Turbomachinery* [1,2]. The coating feedstock is a powder blend containing 60wt% nickel-chromium (Ni-20Cr), 20wt% chromia (Cr_2O_3), 10wt% BaF_2-32CaF_2, and 10wt% silver. The nickel-chromium is a binder, while chromia hardens the material for wear resistance. Silver and the eutectic fluoride are low temperature and high temperature solid lubricants, respectively. The composite powder is thoroughly mixed and fed into a plasma spray gun for deposition. During deposition, the material is heated to a molten or semi-molten state and propelled onto the surface to be coated. The coating is deposited to a thickness slightly greater than required and then ground to the desired dimension and surface finish.

Chemical analysis of heat-treated PS304 microstructures indicated a depletion of chromium from the Ni-20Cr constituent, resulting in a chromium content of about 10wt% [3,4]. Based on this information, one possible reaction could be oxidation of the chromium in Ni-20Cr by the following process:

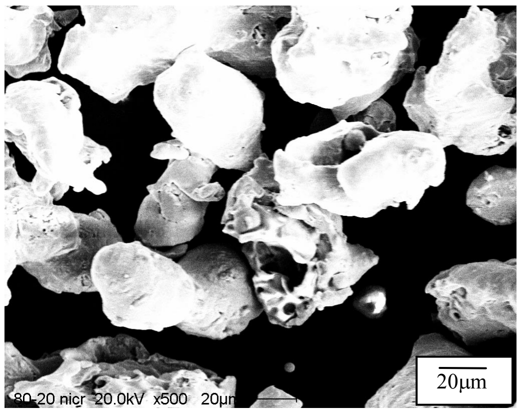
$$2Cr + 3O_2 \rightarrow Cr_2O_3$$

indicating a general depletion of chromium from the Ni-Cr solid solution and formation of chromium oxide. Therefore, a Ni-Cr powder with only 10wt% chromium (Ni-10Cr) was acquired and a modification of PS304, designated *LCR304*, was produced to improve the environmental durability of the coating. In a recent study, LCR304 was shown to have better dimensional stability when exposed to air at 650°C [5]. The purpose of this investigation was to compare the friction and wear characteristics of LCR304 to PS304. The study was conducted by pin-on-disk tests with Inconel X-750 pins on Inconel 718 disks coated by plasma spray with LCR304 or PS304 and by component tests with foil air bearings and plasma spray coated journals.

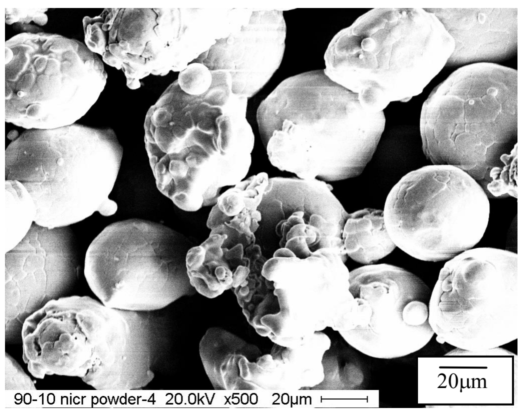
Experimental Materials and Procedures

Materials

Feedstock materials for plasma spray deposition were obtained in powder form. Gas atomized Ni-20Cr (>98% purity) and Ni-10Cr (>99% purity) were obtained from commercial sources. Each powder was classified by screening to retain 44–74 µm particles, shown in Fig. 1. Chromia (>99% purity), fabricated by comminution, was screened to retain 30–44 µm particles, shown in Fig. 2a. Silver powder (>99% purity) was fabricated by gas atomization and classified to obtain 45–100 µm diameter particles (Fig. 2). Calcium fluoride (>99% purity) and barium fluoride (99% purity) were combined at the eutectic composition (68wt%BaF_2-32wt%CaF_2) in a graphite crucible, melted under a moderate vacuum at 1100°C and then cooled under a moderate vacuum. The solidified material was then comminuted into a powder and screened to retain 45-106 µm particles (Fig. 2).



(a)



(b)

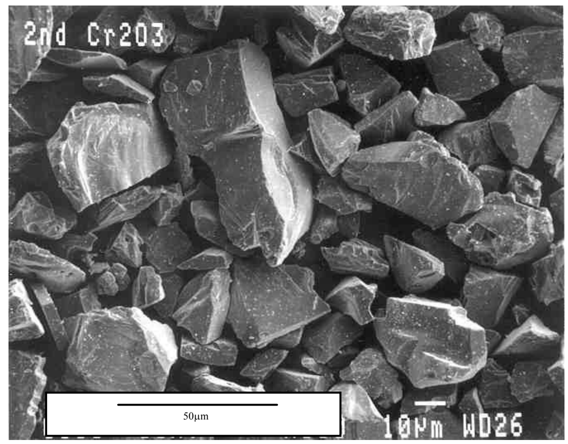
Figure 1: Nickel-chromium powders used in this investigation; (a) Ni-20Cr and (b) Ni-10Cr (original magnification 500×).

Pin-on-Disk Testing

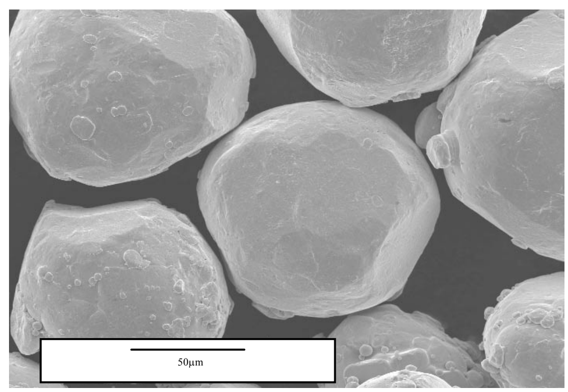
Disk specimens (∅63.5 mm × 12 mm) were fabricated from high temperature resistant metal alloys and ground to within 0.005 mm full indicator movement (FIM) resulting in 0.05 mm typical FIM upon installation in the test apparatus. Cylindrical rider specimens were fabricated from nickel-based superalloys with a 4.76 mm hemispherical tip and a nominal length of 26 mm.

The disk surface to be coated was grit blasted with −60 mesh (<250 µm) alumina. The parameters used during plasma spray deposition are listed in Table 1. For the two coatings, PS304 and LCR304, the feedstock flow rates were approximately 0.5 kg/hr and 0.6 kg/hr, respectively. Approximately 15 passes were necessary to deposit a 0.35 mm coating. To increase coating cohesion strength and dimensional stability, the coating was heat treated at 650°C in air for 24 hours and subsequently ground to 0.25 mm.

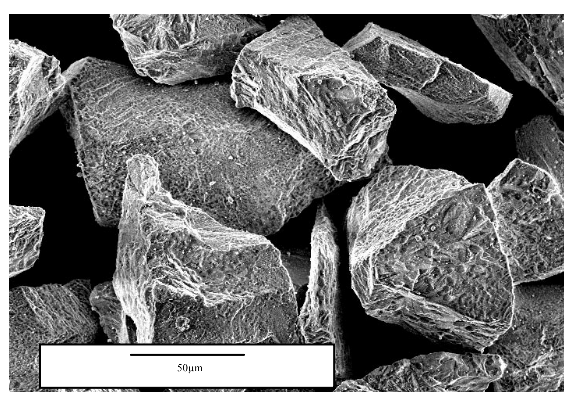
To remove organic residue from cutting and finishing processes, all disk and rider specimens were then heated in air at 150°C for 3 hours, cleaned in ethyl alcohol (95% purity), scrubbed with levigated alumina, rinsed with deionized water (17.8MΩ-cm) and dried at 100°C for 1 hour.



(a) Chromia (Cr_2O_3)



(*c*) *Silver (Ag)*



(*c*) *Eutectic fluorides (BaF_2-CaF_2)*

Figure 2: Chromia (original magnification 600×), silver and fluoride (500×) feedstock powders.

Table 1: Plasma spray deposition process parameters.

Process parameter	Value
Plasma gas flow rate	Ar: 4.2 L/min He: 1.4 L/min
Carrier gas flow rate	Ar: 1.4 L/min
Current	650 A
Voltage	32 V
Gun-to-specimen distance	8-10 cm

Each test was 1 hour in duration at 25, 500 or 650°C with a sliding speed of 2.7m/s and a normal load of 0.5kg. Disks were heated using a low frequency induction coil. The surface temperature was allowed to equilibrate and was monitored 90° ahead of the rider during the test. The friction force was measured through a load cell. Rider wear was measured every 20 min by removing the rider measuring the diameter of the wear scar. Disk wear was determined at the end of the test by measuring the surface profile of the ∅51 mm wear track to calculate the cross-sectional area of the worn material and then multiplying this value by the wear track circumference to obtain the wear volume. The accuracy of the stylus-type profilometer used was within 2% of the calibration block value. The wear factor *K*, a coefficient used to compare the wear of materials normalized for different sliding speeds and loads, was calculated for pin and disk specimens as described in the Appendix. Each test was repeated once.

Foil Air Bearing Testing

Journals for foil air bearing tests (see Fig. 3) were coated by plasma spray deposition and heat treated at 650°C for 24 hours. The coating was then ground to the final dimension (0.25 mm) using a 400 grit resin bonded diamond wheel with mist water coolant on an in-place outer diameter grinder. This grinding step resulted in 0.005 mm FIM for the journal. Then 600 grit SiC abrasive paper was used to finish grind to a typical surface roughness of 0.2 μm R_a. The journals were rinsed with ethyl alcohol and dried with a clean, lint-free cloth before testing. Generation I foil air bearings (38 mm diameter by 38 mm long) constructed with Inconel X-750 sheet metal top foils were prepared by ultrasonic cleaning in ethanol followed by drying with compressed air.

Bearing friction and wear performance was evaluated with a foil air bearing test rig. The rig performed 30,000 start-stop cycles at temperatures ranging from 25 to 650°C with a 10.3 kPa contact stress. A complete cycle typically lasts approximately 20 sec. For the first two-thirds of the cycle, the spindle motor drive is activated and, within a few seconds, the journal accelerates to full rotational speed (14,000 rpm). Above approximately 4,000 rpm, a hydrodynamic air film is formed, which lubricates the journal and supports load [6]. The spindle motor is then deactivated and the journal coasts to a halt during the last third of the cycle. The start-stop torque is characterized by its sharp increase relative to the torque attained during normal operation because of sliding contact between the journal and the foil due to the breakdown of the air film. Bearing torque (tangential force) was measured throughout the test and the torque at the beginning and end of each cycle (start-stop torque) was recorded. The average of five stopping torque measurements was reported at selected intervals for comparison. Due to the time and expense involved in this test, only a single test was performed at 25° and 427°C. The test was repeated once at 650°C and the average value for each result was reported.

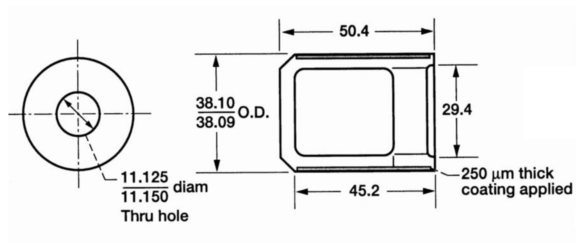


Figure 3: Foil bearing journal dimensions (units in mm unless otherwise specified).

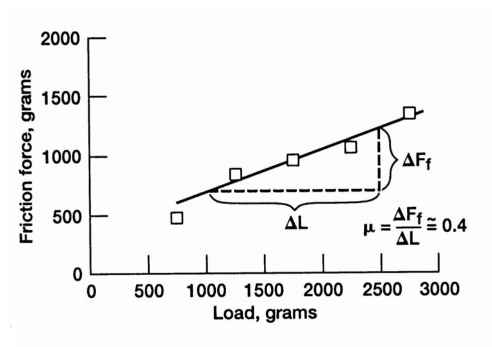


Figure 4: Schematic representation of friction coefficient calculation.

After the start-stop evaluation, the system friction performance was measured by increasing the normal load in 2.45 N increments up to approximately 45 N. The average of three stopping torque measurements was reported for each load. The coefficient of friction was then calculated by two methods. In the first method, the friction coefficient was calculated as the slope of the least-squares fit of friction force as a function of static load, as shown schematically in Fig. 4 [7]. The intercept of this line is the bearing preload, or the spring force within the system due to the designed interference fit between the bearing inner diameter and the shaft outer diameter. Also, the apparent friction coefficient was determined by dividing the measured friction force by the dead weight load. This measurement does not account for bearing preload.

Journal wear was measured with a micrometer at the center and two outer edges of the contact area. Foil wear was measured at the top dead center location of the top foil, which is the location of highest wear during startup and shutdown.

Results and Discussion

In pin-on-disk tests, the coefficient of friction for LCR304 varied from approximately 0.36 to 0.21 as the temperature was increased from room temperature to 650°C, as shown in Table 2. These results were essentially the same as those obtained with PS304 within the given statistical variation [8]. In Table 3, the average values for pin and disk wear with the LCR304 disk coating appear to be generally lower than with PS304. However, other than the measured disk wear at 25°C, the wear data is very similar for both coatings within the stated statistical variation. Disk wear at room temperature is significantly higher for LCR304.

Table 2: Pin-on-disk tribometer friction coefficients (1 hour test at 0.5 kg normal load and 2.7 m/s sliding speed, except where specified); statistical variation is the standard deviation of results from two tests.

Temperature (°C)	LCR304	PS304[a]
25	0.36 ± 0.02	0.31 ± 0.05
500	0.21 ± 0.001	0.25 ± 0.02
650	0.21 ± 0.01	0.23 ± 0.02

a. Tests performed at 0.5 kg (4.9 N) and 1 m/s sliding speed [8].

Table 3: Pin-on-disk tribometer wear factors (1 hour test at 0.5 kg normal load and 2.7 m/s sliding speed, except where specified); statistical variation, where listed, standard deviation of results from two separate tests.

	K_{pin} (mm^3/N-m×10^{-5})		K_{disk} (mm^3/N-m×10^{-5})	
Temp. (°C)	LCR304	PS304[a]	LCR304	PS304[a]
25	0.19 ± 0.2	0.96 ± 0.3	8.56 ± 1.08	4.8 ± 0.3
500	0.003 ± 0.0	0.32 ± 0.5	0.39 ± 0.37	2.8 ± 0.3
650	0.014 ± 0.0	0.38 ± 0.4	0.65 ± 0.20	1.0 ± 0.1

a. Test performed at 0.5 kg (4.9 N) and 1 m/s sliding speed [8].

Table 4 lists the results from foil bearing tests. The friction coefficient decreased as temperature increased from 25° to 650°C as expected. The calculated and apparent coefficients of friction were higher with LCR304 than with PS304. The preload values are given for reference only since they reflect the difference in bearing stiffness due to manufacturing variation. There was no wear of the top foil with LCR304, which is a significant improvement over the wear performance of PS304. However, the LCR304 coated journal wore at 2 to 4 times the rate the PS304 coated journals did as temperature decreased from 650°C to room temperature. For applications that have relatively few startup and shutdown cycles such that wear is not of great concern, but where dimensional stability of the system is very important (e.g. power systems for UAVs or space vehicles), LCR304 could serve as an alternative to PS304.

Table 4: Foil air bearing friction and wear characteristics for journal coated with LCR304 after 30,000 start-stop cycles.

	Calculated friction coefficient[a]		Apparent friction coefficient[b]	
Temp. (°C)	LCR304	PS304[c]	LCR304	PS304[c]
25	0.50	0.22	0.72	0.40
427	0.31	0.21	0.48	0.39
650	0.26	0.16	0.38	0.33

	Foil wear (μm)[d]		Journal wear (μm)[d]	
Temp. (°C)	LCR304	PS304[c]	LCR304	PS304[c]
25	0	46	91	25
427	0	3	18	4
650	0	5	10	5

a. Friction coefficient is the measured friction force divided by the dead weight load (does not account for bearing preload).
b. Values measured at loads from varying from approximately 10 to 30 kPa.
c. Values for PS304 from an earlier investigation under the same conditions [2].
d. Normal load constant at 10.2 kPa.

Conclusions

The purpose of this study was to compare the tribological performance of LCR304 to that of PS304. Based on the results, the following conclusions were drawn:

1. The tribological performance of LCR304 is essentially the same as PS304 in pin-on-disk evaluations.
2. In foil bearing test, the friction and coating wear was higher with LCR304, but LCR304 produced no measurable wear of the bearing top foil.
3. LCR304 is a viable alternative to PS304 for applications requiring high dimensional stability with few cycles, where wear is minimized.

Appendix

The wear factor (K) used in this study is a coefficient that relates the volume of the material worn from a surface to the distance slid and the normal load at a constant sliding speed. The wear factor for the pin is mathematically defined as:

$$K_{pin} = \frac{V}{(S \times W)}$$

where:
$V \equiv$ the volume of the material worn away on the pin in cubic centimeters
$S \equiv$ the total distance slid in centimeters
$W \equiv$ the normal load at the sliding contact in kilograms.

The mathematical representation of the volume of the material worn is:

$$V = 0.167 \times \pi \times H \times \left(3 \times r^2 \times H^2\right)$$

where:
$r \equiv$ the pin wear scar radius
R = original radius of curvature of the pin
$H = R - (R^2 - r^2)^{1/2}$.

The mathematical representation of the total distance slid is:

$$S = 2 \times \pi \times P \times D \times T_r$$

where:
$P \equiv$ the specimen rotational speed (in RPM)
$D \equiv$ duration of test in minutes
$T_r \equiv$ the wear track radius.

The wear factor is also calculated for the disk. This coefficient relates the volume of material worn from the disk to the normal load, the specimen rotation speed, and the duration of the test. The wear factor for the disk is mathematically defined as:

$$K_{disk} = \frac{V_D}{W \times T_r \times D}$$

where:
$V_{disk} \equiv$ the volume of material worn away on the disk in cubic centimeters.

The mathematical representation of the volume of material worn away on the disk is:

$$V_{disk} = 2 \times \pi \times T_r \times \left(\frac{A}{10^8}\right)$$

where:
$A \equiv$ the average cross-sectional wear track area (in μm^2).

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